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LOST THRUST METHODOLOGY FOR GAS TURBINE ENGINE PERFORMANCE ANALYSIS

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ABSTRACT

This paper presents and evaluates a lost thrust method for analysis of thermodynamic performance in gas turbine engines. This method is based on the definition of a hypothetical ideal engine that is used as a point of comparison to evaluate performance of the real engine. Specifically, component loss is quantified in terms of decrements in thrust of the real engine relative to the ideal engine having the same design point cycle. These lost thrust decrements provide a basis for accurately evaluating the performance cost of component losses while simultaneously accounting for all component interactions. The analysis algorithm is formally developed in detail and is then demonstrated for a typical separate flow turbofan engine. Various scenarios are examined and the results of these exercises are used to draw conclusions regarding the strengths and weaknesses of this approach to gas turbine performance analysis.

INTRODUCTION

The objective of this paper is to present and evaluate a method for assessing the impact of component loss on overall engine performance. Component loss is used for two purposes: understanding how much potential gain is left in overall system performance, and understanding which component or thermodynamic process contributes the greatest departure from ideal performance. The former is useful in providing a point of calibration for the analyst in setting realistic performance goals at the conceptual design stage. The latter is useful in identifying specific components likely to yield the greatest improvement in system performance during preliminary design or component improvement programs.

The textbook approach to analyzing the impact of component losses on overall engine performance is to use sensitivity methods [1]. Sensitivities can be used to accurately estimate the system benefit from a unit change in component performance (the thrust loss due to a 1-point decrease in compressor efficiency, for example). Unfortunately, sensitivities do not yield any insight regarding total loss due to a given component inefficiency (for example, reduction in total thrust output due to all aerodynamic losses in the compressor).

A simple way to obtain a rough estimate for total system impact of component losses is to neglect a particular component loss and re-balance the cycle [2]. For example, imagine setting compressor efficiency to 100% and re-balancing the cycle to find the new thrust-specific fuel consumption (TSFC) at constant thrust. The difference between the re-balanced engine performance and the actual engine performance is taken to be the impact of the component loss. This process of re-balancing can be applied to each component in turn to obtain a complete picture of total system impact of component losses. However, an engine is a tightly coupled collection of components. As a result, resetting a component loss impacts not only the performance of the component of interest, but also other components in the re-balanced system. The calculated result is therefore confounded with undesired changes in system performance due to changes in operating conditions of other components in addition to the desired component performance changes.

Another class of methods available for loss analysis are those based on the Second Law of thermodynamics [3]. These methods enable exact calculation of maximum theoretical work available in a fluid at given conditions and assuming a user-prescribed “dead state” reference condition. An appealing attribute of second-law methods is that they provide an unambiguous definition of “ideal” against which to compare the performance of the actual engine. The best-known of these methods is exergy analysis. Unfortunately, exergy is not direct a measure of sensible thrust work available in an aerospace engine [4,5]. As a result, alternative work potential figures of merit that more closely fit the needs of propulsion system analysis are necessary, and are a subject of active research [6].

The *lost thrust method* described in this paper is essentially an extension of an approach developed by Riggins [7], which is in turn related to ideas suggested by Curran and Craig [8]. It is intended to provide information regarding total system impact of component losses while simultaneously avoiding the problem of confounding influences due to component interactions present in the “component perturbation” methods. Further, this method does not require any understanding of work potential or exergy concepts in order to use it.

LOST THRUST METHOD

The lost thrust method works by iterative cycle re-balance. The technique generally starts from the back and sweeps through to the front of the engine. At each step, a single component loss is deleted from the model and the cycle performance is re-calculated. The difference in thrust of the previous iteration and the current iteration is taken to be the impact of that component loss mechanism on overall engine performance. Since the entire model is re-balanced at each step, the component interactions are automatically accounted for without the need for any special action on the part of the analyst. The order in which the component losses are removed from the model guarantees that their interactions are not confounded with component loss. This re-balancing process proceeds until all losses have been removed from the model leaving only the ideal engine having no component losses and the same nominal cycle as the real engine. The advantages of this method are that it can be used with any engine performance model, it requires no special analysis tools to implement, and it provides an accurate picture of the true cost, in terms of lost thrust, of each component loss.

Definition of the Ideal Engine

The lost thrust method is fundamentally a comparison between an actual engine and a hypothetical ideal engine. It follows that the choice of "ideal" has great bearing on the results obtained. The most logical point of comparison for lost thrust method should be the ideal design point cycle.* For a turbofan engine, this would be an engine having the same design point overall pressure ratio (OPR), fan pressure ratio (FPR), turbine inlet temperature (TIT), and extraction ratio/throttle ratio as the real machine, but with all component losses removed, all pressure losses deleted, and so on.

The rationale for choosing the design point cycle as the ideal is that the design point cycle is determined largely by technology limits and by the engine application. OPR and TIT are typically driven by materials and cooling technology limits. FPR, extraction ratio, and throttle ratio are driven by the engine-airframe match (i.e. vehicle mission). The design point cycle is therefore an implicit expression of an ideal cycle subject to current technology constraints and vehicle mission requirements.

A second reason to use the design point cycle as the ideal is pragmatism. The design point cycle is unambiguous. It is a given that the design point cycle must be known prior to embarking on any cycle analysis exercise. Finally, its selection as the "ideal cycle" point of comparison is probably the most useful of all possible choices because the lost thrust analysis results will be referenced to the ideal nominal cycle.

Ordering of Components (Reverse Sweep Method)

It was mentioned previously that the order in which losses are removed from the model is usually from the back to the front of the engine. The reason for this is that it minimizes the impact of component interactions on the analysis results. For example, consider a set of components connected in series: a turbine rear frame, a jet pipe, and an exhaust nozzle in a turbojet engine. Each of these components has a loss mechanism, each being quantified in terms of a component performance figure of merit: rear frame pressure loss, jet pipe pressure loss, and nozzle thrust coefficient, respectively. We desire to estimate the total contribution of each loss mechanism in terms of lost thrust relative to the ideal engine. If the turbine rear frame pressure loss were removed first and the cycle re-balanced (holding total flow and upstream conditions constant), the difference in thrust between the re-balanced and the original machines would be due to several causes. Part of the thrust change will be due to the deletion of turbine frame pressure loss. Another portion will be due to the change in jet pipe pressure drop (because frictional losses will be proportionately higher at higher tailpipe pressures). A third portion of the change will be due to the change in nozzle operating condition and corresponding loss. The tightly coupled nature of the system causes all downstream components to change in response to an upstream change.

Conversely, if the losses are removed from back to front, the confounding between component impacts is avoided. Starting with the nozzle, if nozzle thrust coefficient (C_{FG}) is set to 1.0, the change in thrust of the re-balanced cycle will be due to the nozzle only. Next, holding $C_{FG} = 1.0$ and setting tailpipe pressure loss to 0.0, the model is again re-balanced. The thrust difference between the second re-balance and the first is due to tailpipe pressure loss only. It is not confounded with nozzle loss because there is no nozzle loss. This basic process applies for any set of components connected in series provided that there is no feedback mechanism that could impact upstream conditions.

Components Having Multiple Input/Output Streams

Lost thrust analysis of components having multiple input or output streams is only slightly more complicated than the series connections discussed in the previous section. Continuing with the turbojet example used previously, consider the next upstream component: the turbine. One cannot simply re-set the turbine efficiency to 1.0 and re-balance the cycle. This is because the turbine has two output streams (shaft output and fluid output). The user must therefore provide one additional piece of information describing how the re-balanced energy is to be split between these two streams.

Two options are available: hold the turbine shaft power output constant and allow the turbine exit pressure to rise or hold turbine exit pressure constant and allow shaft power output to increase. We have previously assumed that the engine design point cycle is to be the ideal, which implies that OPR is to be held constant. The preferred option is therefore to hold shaft power constant, allowing the excess energy available in the turbine to be manifested as an increase in tailpipe pressure rather than increased shaft work.

A similar choice is necessary in the next upstream component, the combustor. Specifically, two streams enter the combustor: compressor discharge air and fuel flow. When the combustor heat release efficiency is set to 1.0, one can either hold fuel flow rate constant and allow TIT to increase or hold TIT and allow fuel flow to decrease. The latter option is consistent with the present definition of the ideal cycle.

As a final example, consider the compressor. This component has two streams entering (shaft work and inlet flow). When compressor efficiency is set to 1.0, there are again two options: hold discharge pressure or hold shaft work input.

* In effect, the definition of the "ideal engine" takes the place of the reference or "dead state" conditions used in work potential and exergy-based analysis methods. See Riggins [7].

The ideal cycle assumption implies that discharge pressure (and OPR) should be held constant while shaft work is decreased. This will result in increased tailpipe pressure, due to the reduced turbine extraction requirements.

These simple examples are easily generalized to any component having multiple input or output streams. The rule is: *one additional re-balance assumption is required for each redundant input or output stream*. The guiding principle in selecting these assumptions should always be to select the option consistent with recovering the ideal cycle at the final re-balance iteration.

Cooling and Secondary Flow Circuits

The user's definition of the ideal engine determines how multiple-flow situations in the primary flow path should be handled. However, the multiple-stream situations encountered most frequently in cycle models are those involving cooling flows and other secondary flow circuits. All secondary flow circuits have losses, pressure losses being chief among them. The treatment of these losses in the context of the lost thrust method is not as straightforward as one might assume.

The reason that it is more difficult to account for losses in the secondary flowpath is that these losses straddle the boundary between cycle and components: they can be treated as component losses and analyzed in like manner with any other pressure loss. Alternatively, one could consider the secondary flow system as being an integral part of the ideal cycle definition, implying that they should be held constant in the lost thrust analysis. Additional options are available between these two extremes, the choice being dependent on how one chooses to define the "ideal" engine:

1. *Ignore cooling flows*. The simplest option available is to ignore the cooling flows and simply hold them at their original flow conditions during the re-balance process. This is equivalent to bookkeeping cooling flow losses as part of the ideal cycle and not as a component loss.
2. *Moving extraction point method*. If the pressure loss in the secondary circuit is deleted while the circuit exit pressure and flow rate are held constant, one can move the extraction point of the cooling flow further forward in the compression process. Assuming secondary and primary flow rates are held constant, this will result in a reduction in compressor shaft power required and a reduction of cooling flow temperature.
3. *Imaginary turbo-expander method*. An equivalent option is to assume that there is an imaginary small turbine in the secondary flow circuit that expands the secondary flow to the same exit pressure. The turboexpander energy can be added to the total output of the engine.[†] Again, this implicitly decreases the coolant flow temperature in the turbine, an assumption that may or may not be consistent with one's definition of the ideal cycle.
4. *Deletion method*. Deleting the cooling flows from the "ideal" engine is the opposite extreme of the first option. This method implicitly assumes that the ideal engine uses ideal materials (since there are no cooling flows), and requires the user to make an assumption on how the cycle is re-balanced when the secondary flow is deleted.

[†] Another variant of this option is to hold flow splits constant, delete pressure losses in the secondary circuit, and match the static pressure via isentropic expansion. This implies that the momentum is conserved through the remainder of the model.

The selection of which approach to use depends on the definition of the "ideal" engine. If the ideal engine has no materials temperature limits, the deletion option will yield the most consistent results. If realistic materials limits are assumed in the ideal engine, then the first option is preferred. If the pressure losses are to be part of the component losses but quasi-realistic materials limits are to be enforced, then options 2 or 3 yield the most consistent results.

Basic Algorithm

The main inputs required to perform the lost thrust analysis are a cycle model representing the real engine and a precise definition of the "ideal engine" against which the real engine is to be compared. Obviously, the user must have the capability to modify component performance parameters in the cycle analysis model in order to perform lost thrust analysis. The basic steps in the lost thrust method are very simple:

1. *Run the baseline engine*. These results provide the starting point for the lost thrust analysis.
2. *Define the ideal cycle*. This is done by determining which parameters are held constant and which are allowed to vary in the re-balance process. This includes the treatment of bleed flows for cooling purposes, components having shaft power extraction, and so on. Each component having more than one input or output must have an accompanying re-balance assumption. Also, the overall cycle balance assumptions must be selected at this point: is combustor exit temperature or fuel flow held constant during re-balance?; is total air flow held constant and thrust allowed to vary or is engine thrust held constant during re-balance and engine size allowed to vary?; and so on.
3. *List all losses in the cycle model*. The number of cycle re-balance runs needed to complete the analysis is equal to the number of loss mechanisms in the cycle model.
4. *Order the losses*. It frequently occurs that a single engine has multiple flow paths (core and bypass flows, for example). When this is the case, one must make an assumption as to which stream should be swept of losses first. Unless a specific circumstance should dictate otherwise, the simplest and most logical convention is to start from the innermost and move to the outermost stream, in the same direction as the station naming nomenclature suggested in [9]. This paper therefore uses the convention that losses should be swept from back to front and from inside to outside. Note that multiple flow paths also require

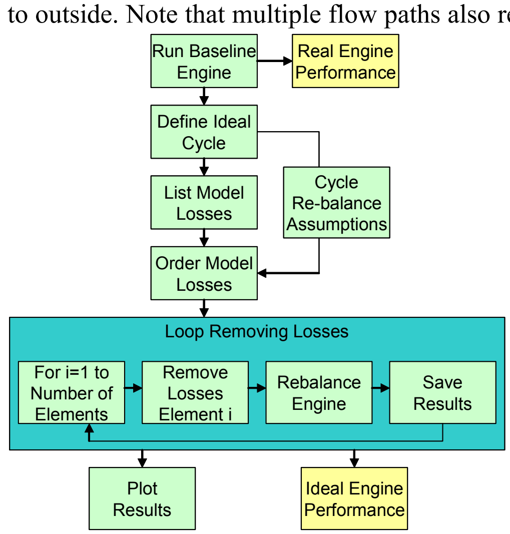

Fig. 1: Basic Lost Thrust Analysis Algorithm

additional assumptions in the re-balance process. For example, should total shaft power into the fan be held constant or should core size be held constant and fan power allowed to vary? Again, the correct choice depends on the definition of "ideal engine."

5. *Iterative cycle re-balance*. Loop through the ordered list of model losses, removing one loss at each iteration:
   a. Remove losses at component i
   b. Rebalance engine and calculate thrust or power output
   c. Calculate and store difference in thrust (or power, or SFC, etc.) from previous iteration
   d. Move to element i+1
   e. Go to a. until all losses are deleted from cycle model
6. Plot analysis results

These steps are depicted in flowchart form in Fig. 1. Note that the byproduct of this analysis is an estimate of the ideal engine performance attainable if all component losses could be eliminated. This provides an interesting point of comparison for the real engine performance and yields considerable insight as to how much performance gain would be attainable if it were possible to build a perfect engine having the same cycle as the real engine. This information is also useful as a "sanity check" when setting performance goals for new engine programs.

A Note on Ordering: Airflow versus Work Transfer

It was mentioned previously that the order in which component losses should be removed from the model is back to front so as to eliminate component interactions from the analysis results. It is natural to assume that this back to front should be in the sense of the flow of air through the engine: nozzle to inlet. However, we should not let our natural bias obscure the fact that there is an alternative point of view one can use to order the loss removal process.

If we take the point of view that the function of an engine is to convert potential energy (stored in the fuel) to thrust work, one can make an argument that the real starting point for thermodynamic losses is with the fuel stream entering the combustor, not with the air entering the inlet [10]. After all, air has no work potential in and of itself; it is only an intermediary used in the process of transferring fuel work potential into thrust work. The fuel contains quantifiable work potential and it is this work potential that is transferred and lost in the various engine components. Thus, if one thinks in terms of work transfer in the engine, the first element is the combustor and the last is the thrust nozzle. In this case, the reverse sweep should be ordered from outside in, with the combustor being the innermost component and therefore the last loss removed.

Fig. 2 contrasts these two points of view for a separate flow turbofan. The left portion shows the order in which the airflow goes through the engine. The component losses would be eliminated starting with the lowest number and moving towards the highest numbered component. Conversely, if work potential sets the order, the arrangement shown at right would result. The order of loss removal is again determined by the numbering of the components. The iteration number depicted in the figures should not be confused with the station numbering nomenclature mentioned previously. The two are not related.

Note that the definition of the ideal engine is the same for both options, as is the real engine (i.e. the analysis starting and ending points are identical). Thus, the difference between the ideal and the real engine performance remains unchanged, though the partitioning of contributions due to component losses is somewhat different.

Both points of view have merit. In most cases, the preferred option is to order the losses according to direction of airflow since it is the point of view most people are familiar with. Also, since most engine performance codes are airflow-oriented in their calculation procedures, ordering in accordance with airflow is generally easier to implement.

The algorithm used herein to order the losses always starts at the core nozzle and then works backwards, going opposite to the flow direction. In the case of turbojet, turboshaft, and turboprop engines, the correct (airflow-centric) order of losses is intuitively clear: it is a straight line from the nozzle to the inlet. For mixed flow turbofans, the same procedure should be followed, but after the high pressure compressor, the bypass duct loss should be next, followed by the fan. For a separate flow turbofan, the nozzle of the fan flow should be ordered following the high-pressure compressor, and then the fan. This order is shown in Fig. 3 for mixed and separate flow turbofans, along with a depiction of the engine layout.

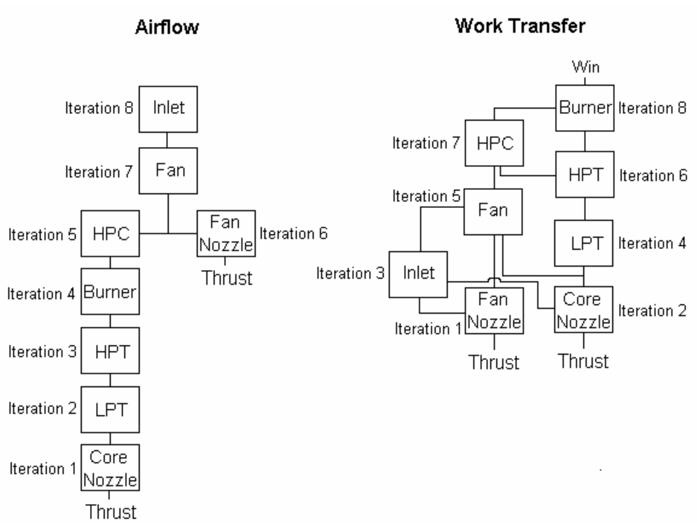

Fig. 2: Airflow versus Work Transfer Depiction of a Separate Flow Turbofan

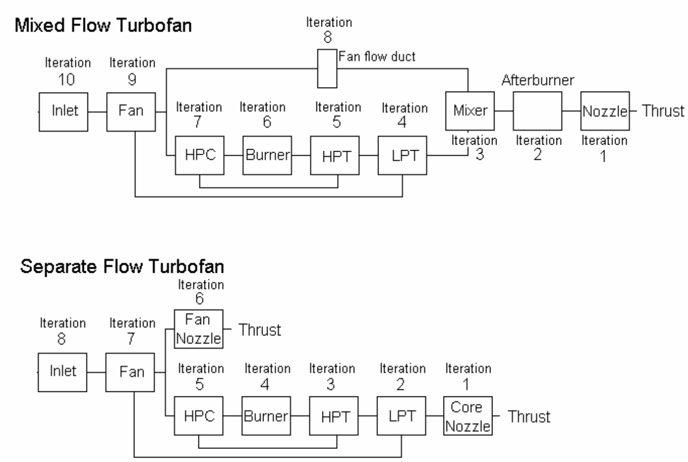

Fig. 3: Suggested Order of Component Loss Removed for Mixed and Separate Flow Turbofans

SEPARATE FLOW TURBOFAN ANALYSIS

Consider a separate flow turbofan (SFTF) engine model as an example to illustrate the application of the lost thrust method. The engine is a generic high bypass commercial turbofan having 26,000 lbs static thrust and a TSFC of 0.230 1/hr. Several cycle design point characteristics for this model are given in Table 1. The assumed component efficiencies for this engine are shown in Table 2 and cooling flow is extracted at a point having 87% of total compressor pressure rise. The engine was modeled using the NEPP cycle code [11] and all calculations are assumed to be Sea Level Static conditions. A schematic diagram of the SFTF cycle model is shown in Fig. 4. All losses in the model are noted in the diagram.

Table 1: Engine Design Point Parameters

Component	Value
Bypass Ratio	5.1
Fan Pressure Ratio	1.6
Low Pressure Compressor Pressure Ratio	2.4
High Pressure Compressor Pressure Ratio	7.755
Combustor Exit Temperature	1755 K
Inlet Corrected Air Flow Rate	362 kg/s
Power Off-take	150 kW

Table 2: Efficiencies and Cooling Flows for Baseline Engine

Component	Efficiency or ΔP/P
Low Pressure Turbine	0.935
High Pressure Turbine	0.930
Combustor	0.995
High Pressure Compressor	0.870
Low Pressure Compressor	0.900
Fan	0.885
Inlet Pressure Recovery	0.990
HPT Non-chargeable Flow	10.55% W25
HPT Chargeable Flow	0.80% W25
LPT Non-chargeable Flow	0.01% W25
LPT Chargeable Flow	0.18% W25

Definition of the Ideal Engine

The definition of the ideal cycle was determined based on the design point cycle definition given in Table 1. Thus, for the fan and the compressors, the pressure ratio is maintained at the same value as the real engine while shaft horsepower input is adjusted to achieve cycle balance. The turbines were rebalanced to hold shaft power output, allowing discharge pressure to increase during cycle re-balance. The combustor exit temperature (T_4) is held constant throughout the re-balance process. The cooling flows are treated as being part of the ideal cycle and are therefore held constant throughout the analysis.

Order Losses for Removal from Model

Following the guidelines introduced earlier, a complete list of all losses in the model (including secondary flow losses) is:

1. C_{FG} Losses (Core)
2. Duct ΔP/P Loss (6→7)
3. Duct ΔP/P Loss (58→6)
4. LP Turbine Chargeable Cooling Losses
5. LP Turbine Loss
6. LP Turbine Non-Chargeable Cooling Losses
7. HP Turbine Chargeable Cooling Losses
8. HP Turbine Loss
9. HP Turbine Non-Chargeable Cooling Losses
10. Burner Pressure Loss
11. HP Compressor Loss
12. LP Compressor Loss
13. C_{FG} Losses (Fan)
14. Duct ΔP/P Loss (13→19)
15. Fan Loss
16. Inlet Pressure Recovery

Since the ideal engine is assumed to include the cooling flows, these are held constant during the re-balance process. To further simplify this analysis example, the contribution of lost thrust due to the various duct pressure drops is assumed to be small in comparison to the loss due to turbomachinery. The pressure drops are therefore ignored, but can easily be included if desired. Furthermore, the very high thrust efficiency of

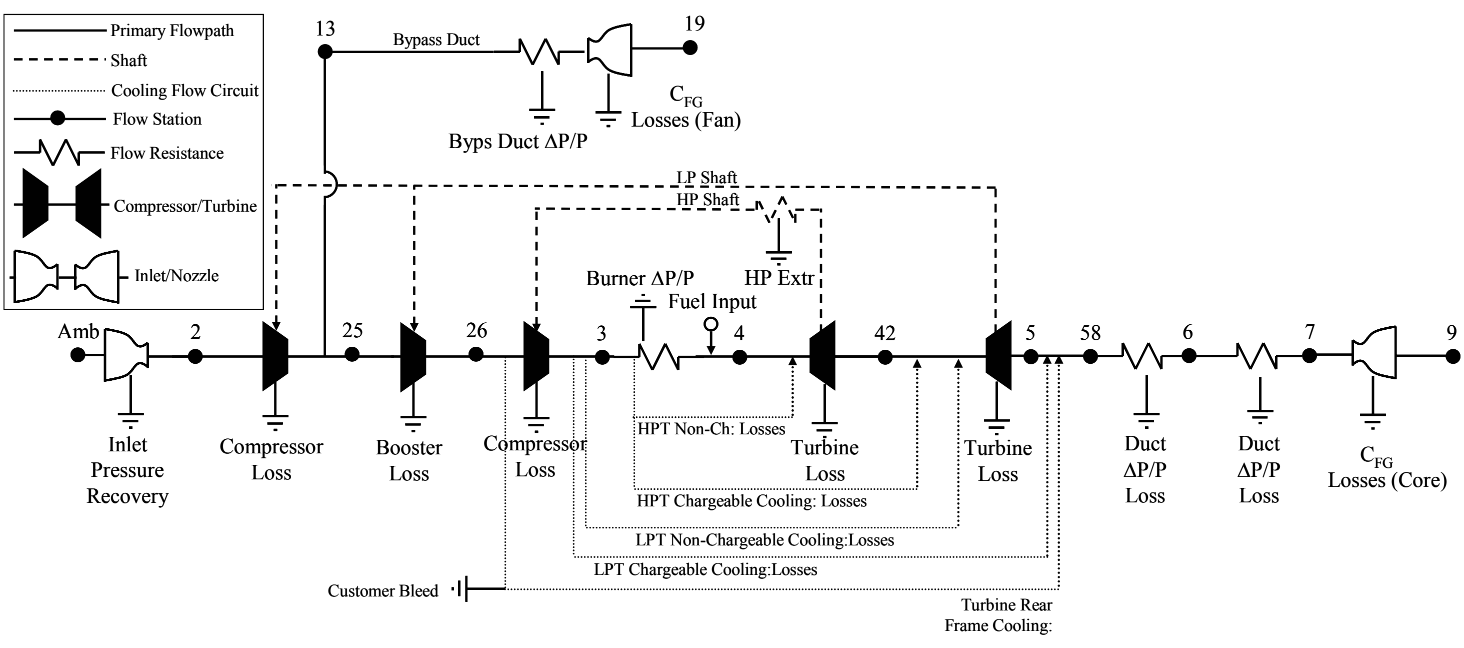

Fig. 4: Separate Flow Turbofan Engine with Cooling Flows

typical high bypass engine nozzles makes their contribution to lost thrust relatively small (generally < 0.5% thrust) and are likewise ignored in this analysis.

Based on these assumptions, the ordered list of component losses and accompanying assumptions is given in Table 3. This list has been reduced considerably from the comprehensive list given previously, but the main contributors to thrust loss are still captured in this analysis. Also, all the key attributes necessary to define the ideal engine are still present in the remaining re-balance assumptions listed in this table.

Table 3: Ordered Losses and Re-balance Assumptions

Loss	Re-balance Assumptions
LPT Efficiency	Shaft Power = Const.
HPT Efficiency	Shaft Power = Const.
Combustion Eff.	Fuel-Air Ratio = Const.
HPC Efficiency	Pressure Ratio = Const.
LPC Efficiency	Pressure Ratio = Const.
Fan Efficiency	Pressure Ratio = Const.
Inlet Recovery	Flow rate, inlet conditions = Const.

Iterative Cycle Re-balance (Constant Engine Size)

Let us assume that engine size is to be held constant during the re-balance process. When this is the case, total engine thrust will increase as each component loss is removed. In order to perform this analysis, the model was set to hold total engine flow rate constant throughout the re-balance process. Power setting was controlled using combustor fuel-air-ratio. The lost thrust increments for the design point (full power) condition are given in Fig. 5. Note that high pressure compressor (HPC) losses contribute the largest thrust loss increment, followed by low pressure turbine (LPT) losses. Also note that the ideal engine yields 14% more thrust for the same flow size as the real engine.

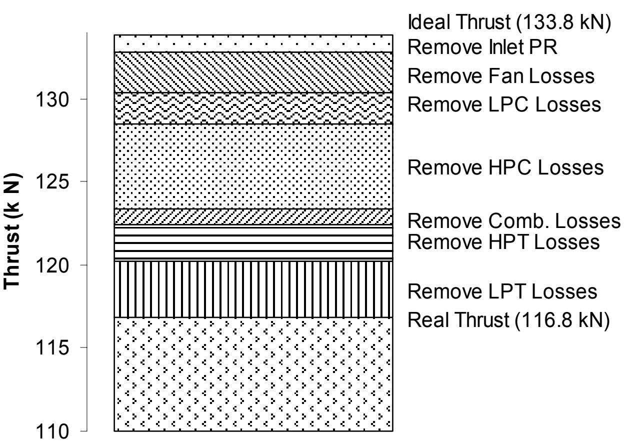

Fig. 5: Lost Thrust due to Component Losses at the Cycle Design Point (Constant Engine Size)

This increased specific thrust also causes an increase in the jet kinetic energy per unit thrust, thereby counteracting some of the TSFC benefit of removing a component loss. This is manifested as converging of the powerhook curves at high power, as shown in Fig. 6. For example, when the compressor losses are removed from the model, it causes a large increase in tailpipe pressure and core nozzle thrust due to the re-balance assumptions used. The higher core jet velocity implies lower propulsive efficiency, counteracting the thermal benefit of ideal compressor efficiency. This interaction can be avoided by holding the ratio of core to fan nozzle pressure ratios constant and varying core size to obtain constant specific thrust.

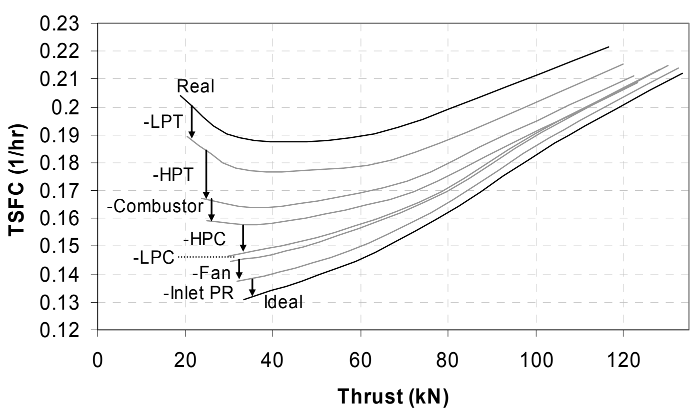

Fig. 6: Lost Thrust Powerhooks (Holding Constant Air Flow Rate and Bypass Ratio During Re-Balance Process)

Iterative Cycle Re-balance (Constant Engine Thrust)

Up to this point, the analysis has held mass flow constant while letting core specific thrust increase (engine size is held constant). This approach makes sense when the objective is to analyze an existing engine, and the desired result is the efficiency of the real engine relative to its ideal. Another method is to hold engine thrust constant throughout the re-balance process while adjusting total mass flow rate. In this case, the size of the core engine would decrease as the re-balance progresses.

In addition to holding constant thrust, let us also modify the re-balance assumptions to hold the ratio of core to fan discharge pressures constant. The powerhook results are as shown in Fig. 7. In this case, there is no "lost thrust" interpretation of the analysis results, only an SFC impact. The powerhooks developed under these assumptions do not converge at high power as in the previous example. This is because the specific thrust of the engine is relatively constant (unlike the previous example) and therefore the propulsive efficiency remains relatively constant throughout the re-balance process. The approach used in Fig. 6 of rebalancing at constant bypass ratio and FPR while allowing core discharge pressure to increase causes a bias that over-emphasizes the impact of the first components and under-emphasizes the last components. In most situations the preferred approach would be to re-balance in such a way as to hold specific thrust constant in order to prevent this biasing.

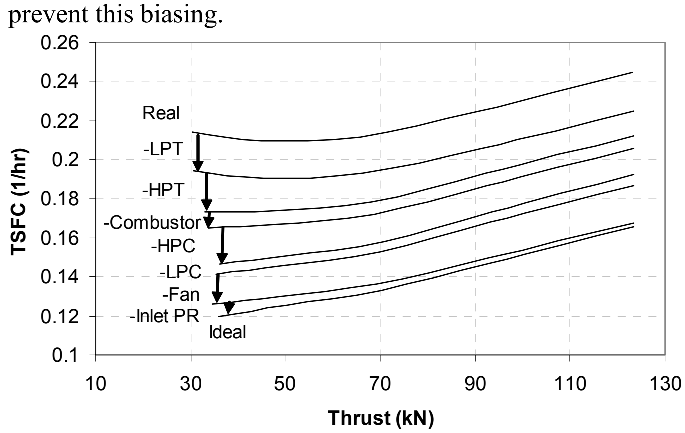

Fig. 7: Lost Thrust Powerhooks (Holding Constant Thrust and Fan/Core Nozzle Pressure Ratios During Re-Balance)

Comparison to Component Perturbation Method

The introduction of this paper mentioned that neglecting a single component loss at a time is an oft-used method for assessing the impact of a single component's loss on overall system performance. Fig. 8 compares the "component perturbation" method to the backwards-sweep lost thrust method at full power. Note that the impact is similar in magnitude for both methods. If one sums the lost thrust increments, the result is the difference between the real and ideal engine thrusts. This is not the case for the perturbation results, due to confounding of component interactions inherent to each perturbation. A comparison of TSFC increments (at constant thrust) as estimated using both methods is shown in Fig. 9. The results are again qualitatively similar, though different in magnitude.

CONCLUSIONS

The lost thrust method is a useful approach to estimate *total system impact* due to component losses and should be viewed as yet another analysis method at the disposal of the propulsion engineer. Specific strengths of this method are:

- The lost thrust method accurately accounts for loss interactions amongst components.

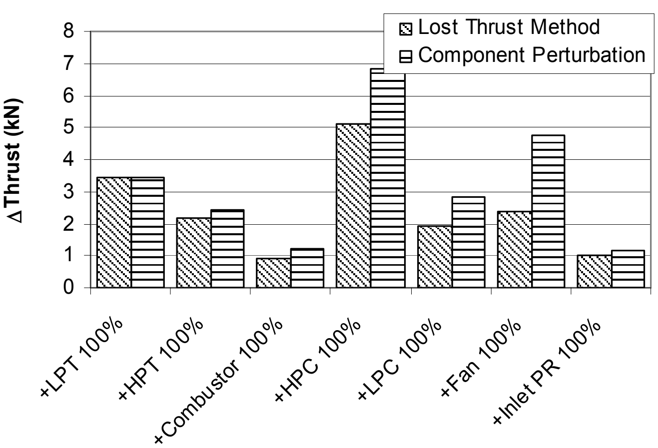

Fig. 8: Comparison of Component Perturbation Results to Backwards-Sweep Results (Lost Thrust Decrement)

Fig. 9: Comparison of Component Perturbation Results to Backwards-Sweep Results (TSFC Increments)

- The summation of all individual losses yields the difference between actual and ideal engine performance. This is not the case for the sensitivity or "component perturbation" methods.
- Only trivial modifications to the existing cycle model are necessary to conduct the analysis.
- The computational requirements are relatively small, and the process could be completely automated if desired.
- Although the lost thrust method uses thrust as the primary figure of merit, other metrics can also be used (TSFC decrements at constant thrust, for example).

Drawbacks to beware of when using this method include:

- There is a significant degree of subjectivity in how one defines the ideal cycle and in the re-balance approach used. In general, the definition of ideal should conform as closely as possible to real limitations and requirements that drive the engine cycle.
- The method used herein is intended for analysis of component performance assuming an ideal cycle. However, the cycle selection is itself dependent on component performance. For example, an improvement in compressor efficiency may enable higher OPRs to be used when compressor discharge temperature is a constraining factor on the cycle. The present work does not address these effects.

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